INVESTIGATIONS OF ELECTRONICALLY CONTROLLABLE TURN OFF CONTROLLED RECTIFIERS

REPORT NO. 4

Contract DA-36-039 SC-85062

DA Project No. 3A99-21-001

FINAL REPORT

30 JUNE 1960 TO 30 JUNE 1961

Prepared For

UNITED STATES ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, NEW JERSEY

By

Rectifier Components Department

GENERAL ELECTRIC

Auburn, New York

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Technical Requirement SCL-2101K, 20 April 1959

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Objective

To perform that research and development work which is directed toward a better understanding of PNPN devices with gate turn-off gain.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

PURPOSE

The objective of this program was to perform research and development work directed toward a better understanding of PNPN devices with gate turn-off gain. The theory developed under U.S. Air Corps Contract No. AF19(604) - 3910, "Active Diodes of the PNPN Type", was expanded and applied to the construction of experimental devices that gave a better insight into the factors affecting gate turnoff of PNPN structures.

SECTION II

ABSTRACT

This report summarizes the work which was performed under a research and development program toward the realization of a high gain gate "turn-off" controlled rectifier. Basically, two types of turn-off structures evolved, 1.) the modified PNPN and 2.) the composite PNPN-NPN. A maximum turn-off gain of 75 was achieved using the modified PNPN structure whereas turn-off gains up to 500 were observed on the composite PNPN-NPN structure. Details of both structures are discussed including theory of operation, fabrication techniques, experimental data and results, measurements and test equipment. Finally, overall conclusions and recommendations are presented based on the work of this program.

SECTION III

REPORTS AND CONFERENCES

A. Reports

Thirteen reports were issued during the period of this contract. These included:

1.) Ten Monthly Progress Reports covering the period 30 June 1960 to 31 May 1961, and

2.) Three Quarterly Progress Reports covering the period 30 June 1960 to 31 March 1961.

B. Conferences

Date	Location	Personnel	Subject
25 July 1960	Syracuse, N. Y.	M. Stern N. Holonyak R. Aldrich J. Flood T. Kendall F. Gentry	Definition of Contract Objectives
4 October 1960	Auburn, N. Y.	W. Mathei F. Gentry J. Flood J. Armata J. Petruzella J. Moyson	Review of Contract Objectives
19 December 1961	Ft. Monmouth, N.J.	W. Mathei J. Armata F. Brand J. Flood F. Gentry T. Kruger	Review of Contract Objectives

B. Conferences (continued)

Date	Location	Personnel	Subject
15 May 1961	Ft. Monmouth, N.J.	J. Flood Conrad Fisher J. Armata T. Kruger	Review of Contract Objectives
8 June 1961	Auburn, N. Y.	F. Gordon Roy Berry J. Moyson	Program Review

SECTION IV

FACTUAL DATA

Chapter 1 - Introduction

At the inception of this program, silicon controlled rectifiers with turn-off gains of 10 and over were not commercially available. At present, low current controlled rectifiers with turn-off gains of 20 and greater are routinely produced. However, controlled rectifiers with turn-off gains of 500 and higher, as described in this report, have yet to find their way into the marketplace.

In order to achieve a controlled rectifier with a turn-off gain of 500 or higher, it was decided to first determine and optimize the capabilities of a simple PNPN structure (Figure 1). By removing an appropriate amount of silicon from the p type emitter of a standard low current controlled rectifier, turn-off gains can be increased greatly. Using this approach and making certain cross-sectional dimension changes, turn-off gains of 20 to 30 were easily obtainable with gains of up to 75 possible.

After optimization of all the other characteristics, the PNPN structure, gate turn-off gains in the 20 to 30 range were designed as being the best compromise, while maintaining all the desirable characteristics. By coupling this structure with a high gain NPN structure on the same header, very high gains were attainable (Figure 2). This composite structure gave turn-off gains up to 500. Further refinements of this procedure, however, would be necessary to extend it to higher current devices.

Chapter 2 - Analysis of the Problem

The construction of a device which can be turned off with a low energy pulse while it is carrying a reasonable amount of current is considerably more difficult than the construction of a high turn-on gain device. This is because a PNPN structure in the "on" state has a built-in, regenerative feedback mechanism which resists attempts to turn it off. Thus, some innovation must be developed which will change the operation from regeneration to degeneration if extremely high gains of 500 and over are to be realized. In order to achieve this goal, work was divided into two stages. The first stage was to achieve the highest practical gain from a simple PNPN structure. The second stage was to couple the PNPN with an NPN on the same header to reach the ultimate aim of 500 or higher. The analytical approaches to each stage follow.

PNPN Structure

To obtain a better understanding of the turn-off mechanism and to choose a suitable scheme for solving the problem, a simple one-dimensional analysis is presented. In Figure 1, a typical four-region, three-junction PNPN structure is shown with contacts applied to the two external regions, and a gate contact attached to one of the base layers. Assuming charge neutrality, negligible multiplication at J_C, and saturation currents small compared to the gate current, one can write:

$$I_{E1}\,\alpha_{PNP} - I_g = (1-\alpha_{NPN})\,I_{E1} \tag{1}$$

$$I_{E1}\,\alpha_{NPN} = (1-\alpha_{PNP})\,I_{E2} \tag{2}$$

Solving for I_{E2}:

$$I_{E2} = I_g \frac{\alpha_{NPN}}{\alpha_{NPN} + \alpha_{PNP} - 1} \tag{3}$$

and the turn-off gain is

$$\frac{I_{E2}}{I_g} = \frac{\alpha_{NPN}}{\alpha_{NPN} + \alpha_{PNP} - 1} \tag{4}$$

In order to determine the requirements for turn-off, the device is considered to be in the conducting state with a load current flowing which is determined principally by the supply voltage and the load resistance. The alphas, therefore, will adjust themselves by means of junction J_C which is in forward bias to the point that exactly enough "base current" reaches each base to supply minority recombination current so that the current flow is maintained. If current is removed from one of the bases, the load current will drop unless the alphas can readjust (increase) themselves. For a given load current, there is a maximum value possible for each alpha. As the gate current flow is increased, α_{NPN} will decrease until $\alpha_{NPN} + \alpha_{PNP} < 1$, at which time the device will switch to the off state. The relationship between the alphas and current is determined by a number of parameters.

Basically, alpha is composed of two parameters, γ the emitter efficiency and β the transport factor. Alpha is simply the product of these two quantities ($\alpha = \gamma\beta$). γ is determined by the relative impurity concentrations on the two sides of the junctions and for not too high or too low injection levels is given by equation 5.

$$\gamma = \frac{1}{I + \frac{\sigma_B W_B}{\sigma_E L_E}} \tag{5}$$

where L_E is the diffusion length of the minority carriers on the emitter side of the junction, W_B is the base width, σ_B and σ_E are the conductivities of the base and emitter regions. The emitter efficiency is also determined by the amount of recombination in the barrier,which in turn, is determined by the lifetime of the material. Another method for controlling the emitter efficiency is the geometrical addition of shorting contacts at the edge of the emitter to base junction, thus lowering the effective emitter efficiency by shorting out part of the junction.

The transport factor, β, is determined primarily by the lifetime and the width of the base region being considered. However, as the current passing through higher resistivity base material increases, the current tends to create a field within the base region which adds to the effective diffusion lengths and thus increases β. Hence, if the device is to turn-off with any appreciable gain, it would be advantageous to restrict the maximum value that α_{PNP} can attain by making the emitter efficiency of J_{E2} quite low.

Obviously, equation (4) only holds to the point where $\alpha_{NPN} + \alpha_{PNP} - 1$ approaches zero. Once the device is in the "on" state, I_{E2} is no longer determined by equation (4) but by the external load resistance. The equation can still be considered to hold true in the "on" state with the assumption the α functions adjust themselves by the redistribution of the charges in the two bases and by the fields set up in these bases. The α functions will vary with gate current. For a fixed gate current, however, the first part of equation (2) will have a minimum possible value. If this minimum value is such that

$$\frac{\alpha_{NPN}\, I_g}{\alpha_{NPN} + \alpha_{PNP} - 1} > I_{E2} \qquad (6)$$

the device will turn off. This becomes more evident if equation (6) is rewritten as

$$I_{E2} > \alpha_{NPN}(I_{E2} - I_g) + \alpha_{PNP}\, I_{E2} \qquad (7)$$

This relationship shows that the collected current at J_C is smaller than the current determined by the load. This means the device is again limiting the current and is in the "off" state. Turn-off gain can thus be defined as

$$\beta \text{ off} = \frac{I_{E2}}{I_g} = \frac{\alpha_{NPN}}{\alpha_{NPN} + \alpha_{PNP} - 1} \text{ min.} \qquad (8)$$

It should be noted that the minimum value of the β function corresponds to the maximum values of α_{NPN} and α_{PNP}, or the values as they actually would be without interaction between the junctions. This means a curve may be drawn with the variations of the alphas as a function of current, and the turn-off gain analyzed from a graph such as Figure 3. The variations of current amplification factors have been known for a long time. Several explanations have been proposed in the literature (References: 1 through 5).

From equation (8) it can be seen that the turn-off gain is inversely proportional to the height of the cross-hatched area of Figure 3. Note that for $I_C = I_A$, point A represents the holding current. Obviously, at this point the turn-off gain is essentially infinite. Starting from point A the gain should decrease and reach a constant value and at some other point both alphas decrease below their maximum value and the gain increases. At some higher current, the current in the high resistivity N_2 region starts increasing α_{PNP} because of field-aided diffusion, and the turn-off gain will increase or decrease depending on the relative variation of α_{PNP} and α_{NPN}. Units were made that showed the characteristics of Figure 4. If α_{PNP} does not increase with increasing current, the sum of the two alphas will be equal to one at the two currents I_A and I_B (Figure 3). This explains Figure 4. Between I_A and I_B the device is a typical PNPN structure in the "on" state. The current saturates at I_B, since the sum of the alphas is less than one beyond this point.

It also is clear that if junction J_1 is made smaller, the current density will increase with respect to J_3. The result is that the α_{NPN} curve in Figure 3 is shifted to the left and the shaded area becomes narrower. This results in higher turn-off gains and has been observed on some units by reducing the area of J_1 without reducing the other junction areas.

The following is a description of the probable turn-off mechanism. In the low impedance state all three junctions are in forward bias. The forward bias of junction J_2 (Figure 1) keeps balance between α_{PNP} and α_{NPN}; i.e. it serves to reduce the net collected current through J_2, making it equal to the total load current. When a current, I_2 (Figure3b), is allowed to flow, the current density through J_1 decreases and fewer electrons are collected at J_2. As long as

$$I_A = \frac{\alpha_{NPN}\, I_g}{\alpha_{NPN} + \alpha_{PNP} - 1}$$

the unit will stay on. While the injected carriers from J_1 decrease, $I_A - \alpha_{NPN} I_C + \alpha_{PNP} I_A$ becomes smaller, and junction J_2 has to inject less holes toward J_3 and less electrons toward J_1 in order to maintain equilibrium. This means the forward bias across J_2 should decrease. This has been observed and measured indirectly. Some units were turned on, and the voltage between anode, cathode and gate terminals were measured with the gate disconnected. The gate circuit was then closed and an increasing gate current was allowed to flow out of the unit. (See Data Section, "Voltage Drop Measurements During Turn-Off"). As can be seen, the voltage between gate and anode increased more and more as the gate current was increased. This is presumably due to the voltage drop across J_2 returning to reverse bias after the forward bias has decreased to zero.

It seems possible to displace the two alpha curves of Figure 3 with respect to each other so that the increase of gain with current can be changed. The turn-off gain at low current level, however, is still dependent on the value of α_{NPN} max. + α_{PNP} max. -1. This value could be made smaller by means of reducing one of the alphas. However, this would also result in an undesirable increase in holding current. With simple PNPN structures it would be very difficult to obtain turn-off gains greater than 75 with a reasonable holding current.

Compound PNPN-NPN Structures

Reference is made to the structure presented in Figure 5. In the equivalent arrangement indicated in Figure 5b with the polarities as shown as base current, I_{g2} will flow into the base of structure (1) causing collector current $I_C = \beta_1 I_{g2}$ to flow. This collector current will have two alternative paths; one through the collector resistance, R_c, and the other through the forward biased junction, J_4. The manner in which the current is distributed will depend on the voltage drop caused in R_c; basically, it is equivalent to a parallel arrangement of a resistor and a PN junction. Refer to Figure 5c. If $\alpha_2 I_{C2} > I_{g2}$, where I_{g2} is the base current necessary to keep structure (1) in saturation, and if $(1 - \alpha_2) I_{C1} > I_{B2}$ where I_{B2} is the required base current to keep structure (2) in saturation, then no gate current (I_g) is required to maintain the current flow and the structure is "on".

The collector resistance, R_c, in structure (1) is dependent on the distribution of the current. Because of the base biasing effects in the P_1 base, only a small part of the emitter will operate at high injection, and because of the high resistivity in layer N_2 this will result in high values of R_c.

For turn-off, a negative bias is applied to G making I_g negative. If I_g is increased, $\alpha_2 I_{C2} - I_g$ will become smaller than I_{g2} and the device will turn-off.

The fact that α_2 has to be very low to obtain a reasonable gain with this structure makes a lateral flow necessary causing a high forward drop. Since the gain of this structure is also limited to a value of less than 100, it does not appear to be advantageous over the simple PNPN structure.

Reference is now made to the structure presented in Figure 7. With the bias as shown in Figure 7b, structure (2) is a standard controlled rectifier with a forward biased junction, J_1, in series. With sufficient positive bias to gate, G, this structure will switch to its low impedance state. Junction J_2 will be a high parallel impedance across structure (2) because it is a reverse biased junction. The current flowing through structure (2) will act as base current for the transistor structure (1) and the forward drop across structure (2) will be the collector bias for J_2. If the transistor (1) has an appreciable current gain, most of the load current, I_L will flow through structure (1). The collector current for structure (1) is equal to:

$$I_C = \frac{\alpha}{1 - \alpha} I_{CR} = \beta I_{CR}$$

assuming a β equal to 50, then

$$I_L = I_C + I_{CR}$$

$$= 50 \, I_{CR} + I_{CR} = 51 \, I_{CR}$$

Refer to points A and B of Figure 6. If the controlled rectifier structure has a turn-off gain of 20, a current, I_{CR}, can be turned off with a negative gate current of .05 I_{CR}, and since the transistor structure will not conduct any appreciable current without base current I_C, a current of 51 I_{CR} is actually turned off with .05 I_{CR} making an overall gain of $\frac{51 \, I_{CR}}{.05 \, I_{CR}}$ or 1020.

With cascading arrangements, even higher turn-off gains would be possible. The main considerations for a given design would be dictated by the requirements placed on the breakdown voltage, and the impedance ratio of the high to low impedance states. It should be noted that the leakage current of the controlled rectifier would be amplified by the transistor, so that the leakage current of a composite structure shown in Figure 7 would be expected to be higher than that of a standard device.

References:

1. J. L. Moll, M. Taneubaum, J. M. Goldey, and N. Holonyak, PNPN Transistor Switches, Proc. I.R.E., Vol. 44, September 1956.
2. A. K. Jonscher, PNPN Switching Diodes, Journal of Electronics & Control, Vol. 3, December 1957.
3. I. M. Mackintosh, Three Terminal PNPN Transistor Switches, AIEE-IRE Semiconductor Devices Research Conference, Boulder, Colo., July 1957.
4. C. J. Sah, R. N. Noyce, and W. Shockley, Carrier Generation and Recombination in p-n Junction Characteristics, Proc. I.R.E., Vol. 45, Sept. 1957.
5. J. A. Hoerni and R. N. Noyce, PNπN Switches, Convention Record of I.R.E. Wescon 1958, Part 3.

Chapter 3 - Discussion of Devices Constructed

Simple PNPN Structures

Initial work was directed toward modification of a standard all diffused 0.5 ampere controlled rectifier so as to improve the gate turn-off gain. Equation (4) in Chapter 2 tells us the proper combination of alphas that will result in a high turn-off, or ($\alpha_{PNP} + \alpha_{NPN}$-1) as small as possible with α_{NPN} as large as possible. The first attempts in the laboratory were to make α_{PNP} as small as possible. This was accomplished by taking conventional controlled rectifier structures (Figure 1) and removing sufficient material from the bottom "p" region to give a higher turn-off gain. Because of the approximate error function distribution of doping impurities in this layer, removal of material results in lowering the concentration of gallium in the emitter. This results in a narrow emitter with a low hole concentration, thereby reducing the emitter efficiency and consequently α_{PNP}.

By rewriting equation (5) and substituting W_E for L_E (because $W_E < L_E$), one obtains the equation

$$\gamma = \frac{1}{1 + \frac{\sigma_B W_B}{\sigma_E W_E}} \qquad (10)$$

Thus it is apparent that in order to obtain a low γ, it is advantageous to reduce both σ_E and W_E. With this reduction in emitter efficiency, α_{PNP} is thereby reduced. It should be noted, however, that this reduction is substantially independent of anode current.

Typical data on structures built as described above are presented in Figure 8. The non-uniformity in the results is probably due to differences in lapping depths. Since the distribution of gallium impurities for these structures is quite steep near the junction (gallium diffusion depth about 2 mils) only a slight variation in lapping depth, less than .1 mil, will make a large difference in α_{PNP} and hence affect the turn-off gain. Also, excessive alloying of gold during mount down to header will also severely affect turn-off characteristics.

Figure 8 shows the turn-off gain as a function of load current for a device from the initial group of units. Two situations are worthy of note here; first, the sharp decline in gain from infinity at the holding current, and second, the more gradual rise of gain with increased load current. As seen from the data, this curve is typical of the devices fabricated by this method. With reference to the first situation, the sharp decline in gain is to be expected since the turn-off gain is infinitely high at the holding current. This gain would be expected to decrease until it reaches some constant value. This is true, since at the holding current the sum of α_{NPN} and α_{PNP} is just one; a small decrease in either emitter current will make the sum less than one and the unit will then switch off. For a very limited application and where an unusually high turn-off gain is required, it may be useful to design this holding current to be close to the operating current. For industrial use or in more general applications, however, this is not a practical solution. With reference to the increase of gain with the increase of load current, this can be explained by the decrease of α_{NPN} beyond its maximum value. This may account for the decrease of $\alpha_{NPN} + \alpha_{PNP} - 1$.

One fault in making turn-off units from standard controlled rectifier structures is the limitation imposed on the load current level that can be controlled due to the transverse resistance in the P-type base width. To overcome this, the structure in Figure 9 was attempted. This structure was found to be the most successful of the various simple PNPN structures investigated. By employing two separate gallium diffusion stages, the diffusion gradient of gallium in the top P-layer is made steep and the bottom P-layer gradual. This provides a low resistivity P-type base width to minimize transverse resistance while permitting better control of the injection efficiency on the anode side. Several units were constructed with varying amounts of the bottom P-layer removed to determine the optimum thickness. The results of these experiments may be seen in Figure 10. If the increase in gain with load current is compared with those from the initial group, Figure 8, the increase in gain is found to be less pronounced. This is attributed to α_{NPN} which was found to be lower in the second group. The decrease of alpha versus current beyond the maximum point can be expected to be greater for high alpha NPN units than for low alpha units.

Assuming α_{PNP} remains constant, $(\alpha_{PNP} + \alpha_{NPN} - 1)$ will decrease more sharply with high values of α_{NPN}, thus accounting for the reported results.

In an effort to more positively determine the mechanisms which contribute to turn-off, a number of devices corresponding to the structure shown in Figure 11 were constructed. These structures had a wide N-type base width of .0055 inch in order to reduce the transport factor and thus to reduce α_{PNP}. The P-type base width was varied to determine its effect on turn-off gain. The turn-off gain did not change much as the P-type base width was varied from .0008 inch to .0005 inch. This is due to the fact that α_{NPN} remained relatively constant in each case. It was observed that the upper limit of load current which could be turned off was seen to decrease when the P-type base width reached .0004 inch. This is attributed to the corresponding increase of the transverse resistance in the P-type base width, resulting in emitter to base breakdown. It was also observed that with .0009 inch bottom P region removed, the devices saturated at higher current levels. This effect was not observed in the structure of Figure 9 because of a much higher transport factor.

One of the problems associated with lowering α on the anode side is the increase of forward drop during the on state. This condition results from the necessity for more majority carriers to transverse the N type base layer as α drops. To lower this field drop in the p-type base layer, lower resistivity bulk material was used. However, no dramatic change was observed.

A stud mounted scale-up version of the 1/2 ampere structure to a 3 ampere structure was attempted toward the end of the program. Some difficulty was encountered in processing which contributed to low voltage units. A typical curve for these units can be found in Figure 12. A few units, however, exhibited good promise for extension of this process to larger devices.

Two methods which were aimed at simplifying structural fabrication were evaluated. One method which involved the use of low concentration gallium diffusion for the anode P layer did not yield consistent results due to poor reproducibility of the novel low concentration gallium diffusion process.

The second approach to obtaining a lower bottom alpha, that of mount down by deep gold alloying, also gave discouraging results. Very low turn-off gains were obtained due to problems encountered in trying to overcome irregular wetting inherent in the gold alloying process.

Compound Structures

In an effort to improve the turn-off gain of the controlled rectifier beyond the gains of the simpler structures, three runs having the structural representation depicted in Figure 5a were made. The object of such a structure was to cause the hole injection from the partially shorted anode to become concentrated on the right hand side of the device by the field built up by the electron majority carrier current in the N_2 region. Similarly, the electrons injected from the N_1 region would also be forced toward the right hand edge of the cathode emitter. When current is removed from the gate, the electrons injected from the N_1 region would be forced toward the left hand side of the device, thereby lowering the transverse biasing effect at the anode junction and causing the sum of the alphas to be reduced below unity to turn the device "off".

The units of the first run broke down at less than 10 volts in the forward direction due to a narrow P_1 base width. None of the units could be turned off except at very low current levels. The P_1 base width in the second run was increased from .1 mil to .4 mil. These units turned on easily, but could not be turned off with a gain of over 5, indicating too much injection from the shorted P_2 emitter. After removing about .6 mil from the shorted emitter side, the gains were increased to 20. To obtain a more favorable current distribution across the cathode emitter junction, the P_1 base width was further increased from .4 mil to .7 mil. However, this proved fruitless, since in going to a thicker P_1 base width alpha NPN was reduced appreciably, leading to devices with high turn-on currents and high holding currents. Most of these units had gains of less than 10.

The above results can be explained in the following manner. In order to obtain a very high top alpha, the P_1 base width in the first run was made so thin that it resulted in a current distribution across the emitter with a very sharp peak to the right. This, unfortunately, also resulted in a high voltage drop in the high resistivity N_2 layer. Because of the increase of alpha PNP with field (field dependence of diffusion lengths of holes in the N_2 region, Reference 1 and 2) the decrease in alpha NPN may be over-compensated, thus preventing the sum of the two alphas from becoming less than one. Since in the second run alpha NPN was lower, the sum of the alphas was reduced to less than one inspite of the increase of alpha PNP. This explains the current limiting action at higher current levels. The low turn-off gains of the third run are attributed to an even lower alpha NPN. Lowering of the bottom alpha in this case gave units that could not be turned on.

Since the turn-off gain of the structure in Figure 5 appeared to be limited to the gain of a single transistor, an additional stage of amplification was required to reach the turn-off goal of 600. One way of achieving this goal is the structure shown in Figure 7a. To prove the feasibility of this device, the equivalent circuit in Figure 7b was constructed using an NPN transistor having a beta of 100 and a turn-off gain of 20. Such an arrangement produced gains up to 2000. The attainment of the structure of Figure 7a with a high breakdown voltage and low saturation voltage drop would be a difficult task. A simpler approach to the same end would be the structure of Figure 2. A few of these devices were constructed and yielded very high turn-off gains, as evidenced by the curves presented in Figure 13. In order to obtain a turn-off gain of 600, a transistor having a beta of 30 and a controlled rectifier having a gain of 20 were used. However, it would be more desirable to use a transistor with gain of 10 and controlled rectifier with a gain of 60. This would permit higher breakdown voltages and less amplification of the leakage current of the controlled rectifier.

<u>References</u>:

1.) R. W. Aldrich and N. Holonyak, <u>Multi-Terminal PNPN Switches</u>, Proc. I.R.E., Vol. 46, pp. 1236-1239, June 1958.

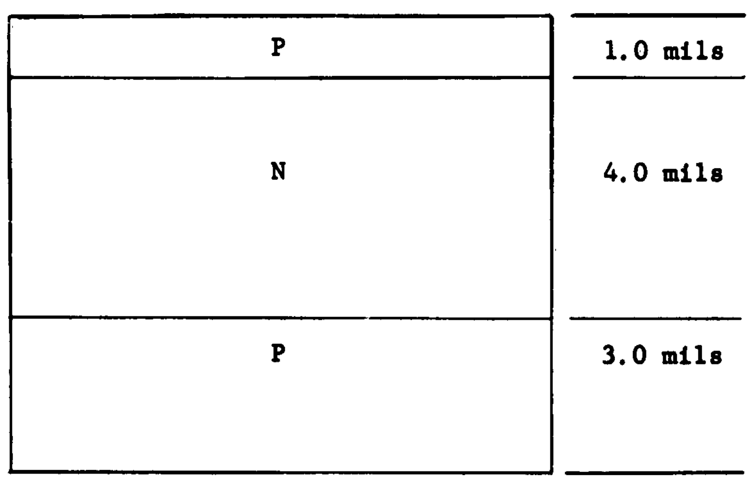
2.) J. A. Hoerni and R. N. Noyce, <u>PNπN Switches</u>, Convention Record of I.R.E. Wescon 1958, Part 3.

Chapter 4 - Device Assembly

All devices (except for a few stud-mounted units late in the program) were housed in standard TO-5 packages. A description of the entire method of fabrication for a typical PNPN turn-off device follows. (Refer to Flow Chart, Figure 14).

Pellet Fabrication:

The controlled rectifier pellet should approximate the structural dimensions shown in Figure 9. N-type silicon having a resistivity of 15-20 ohms-centimeter was chosen as starting material for most structures. This material is capable of giving avalanche breakdown voltages of over 500. The silicon billet was saw cut into wafers 18 mils thick. The wafers were then rough lapped, finish lapped and etched to a thickness of approximately 12 mils. Next, the wafers were gallium diffused. After gallium diffusion, one P-layer was completely removed by lapping so that a PN structure remained. This PN structure was then gallium diffused again to give the following structure:



The wafers were then oxidized to give a film thickness of 10,000 Å. Stripe patterns of .045" bare silicon and .025" oxidized silicon were made on one side of the wafers by spray masking with wax, and subsequent removal of the oxide in concentrated hydrofluoric acid. The wafers were then phosphorous diffused to a depth of .7 mil. This completed the final wafer structure except for reduction of the bottom P-layer to the desired thickness to give optimum device characteristics.

The exact thickness of the bottom P-layer was defined by the final geometry of the wafer and the resistivity of the original material. It was best determined experimentally by lapping until the desired electrical characteristics were obtained. The wafers were then oriented and wax sprayed, and subsequently etched into pellets .060 inch x .070 inch. All etching throughout the process was carried out in CP_6 solution. (CP_6 has the following composition by volume: 5 parts concentrated nitric acid, 3 parts concentrated hydrofluoric acid, and 3 parts concentrated acetic acid.)

Pellet Mount-Down

Pellet mount-down was accomplished in a hydrogen bell jar at approximately 500° C. Since the TO-5 headers used had a gold plating thickness of .15 mil, gold penetration during mount-down was restricted to approximately 0.1 mil.

Lead Attachment

The attachment of the leads was made either by thermo-compression bonding or by ultrasonic bonding. Both methods gave equally satisfactory results. In the case of thermo-compression bonding a Kulicke and Soffa Wire Bonder, Model 401 was used. Bonding of 5 mil diameter gold wires directly to the silicon was accomplished at a temperature of 350° C under hydrogen coverage. Cleaning of parts in this operation was found to be very critical. The surface of the silicon was prepared for bonding by etching in CP_6, immediately prior to bonding, and the gold was degreased in acetone.

The attachment of 10 mil diameter aluminum wire was accomplished with a Sonobond Ultrasonic Welder. Degreasing of parts in acetone was found to be beneficial.

Welding of the leads to the posts was performed with a Hughes Stored Energy Power Supply, Model VTW-28B and a Hughes Model VTA-42 Precision Weld Head.

Varnish and Bake-out

After the attachment of the leads, the sub-assemblies were given a three second clean-up etch in CP_6, and then followed by several rinses in deionized water and acetone. A thin coating of DC-997 varnish was then applied and the sub-assemblies allowed to stand at room temperature for about four hours before a 24-hour bake-out in a 200° C oven under nitrogen coverage.

Capping

Capping of sub-assemblies was performed on a Resistance Welder under dry nitrogen coverage.

Chapter 5 - Measurements and Test Equipment

Direct current measurements were made in a simple circuit as shown in Figure 15. It was found for turn-off the battery in the gate circuit could be eliminated and the same current for turn-off measured up to a certain load current).

The dynamic turn-off measurements were made with a type 575, Tektronix Transistor Curve Tracer modified to provide a collector sweep voltage; that is, A.C. instead of pulsating D.C. The device was connected with the cathode to the ground terminal, the gate to the collector terminal, and the anode to the base terminal (see Figure 16). Photographs of some turn-off curves are presented in Figure 17. The horizontal axis gives the anode current and the vertical axis the gate current. In the negative direction the termination of gate current is seen as a function of anode current. These points give the turn-off current and consequently the turn-off gain of the devices. The curvature of the gate current lines indicates the decrease of anode current just before turn-off.

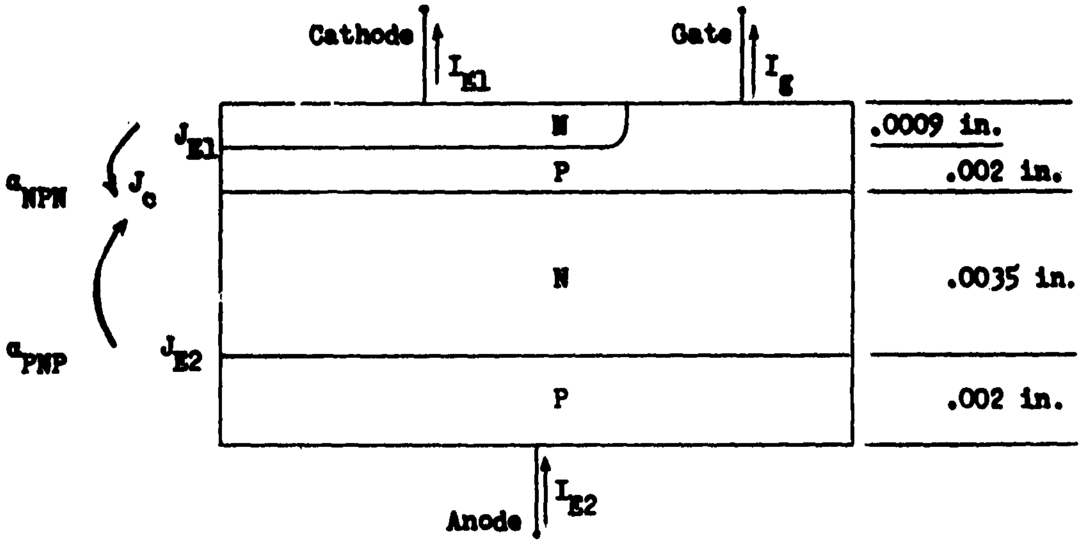


Figure 1- PNPN Structure

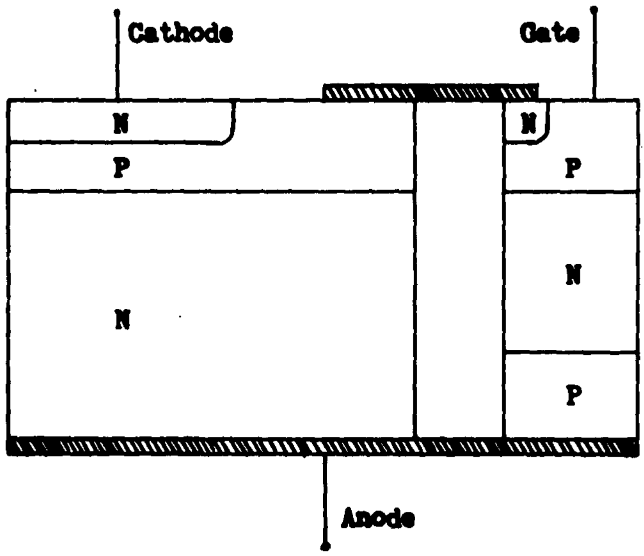


Figure 2- Composite PNPN-NPN Structure

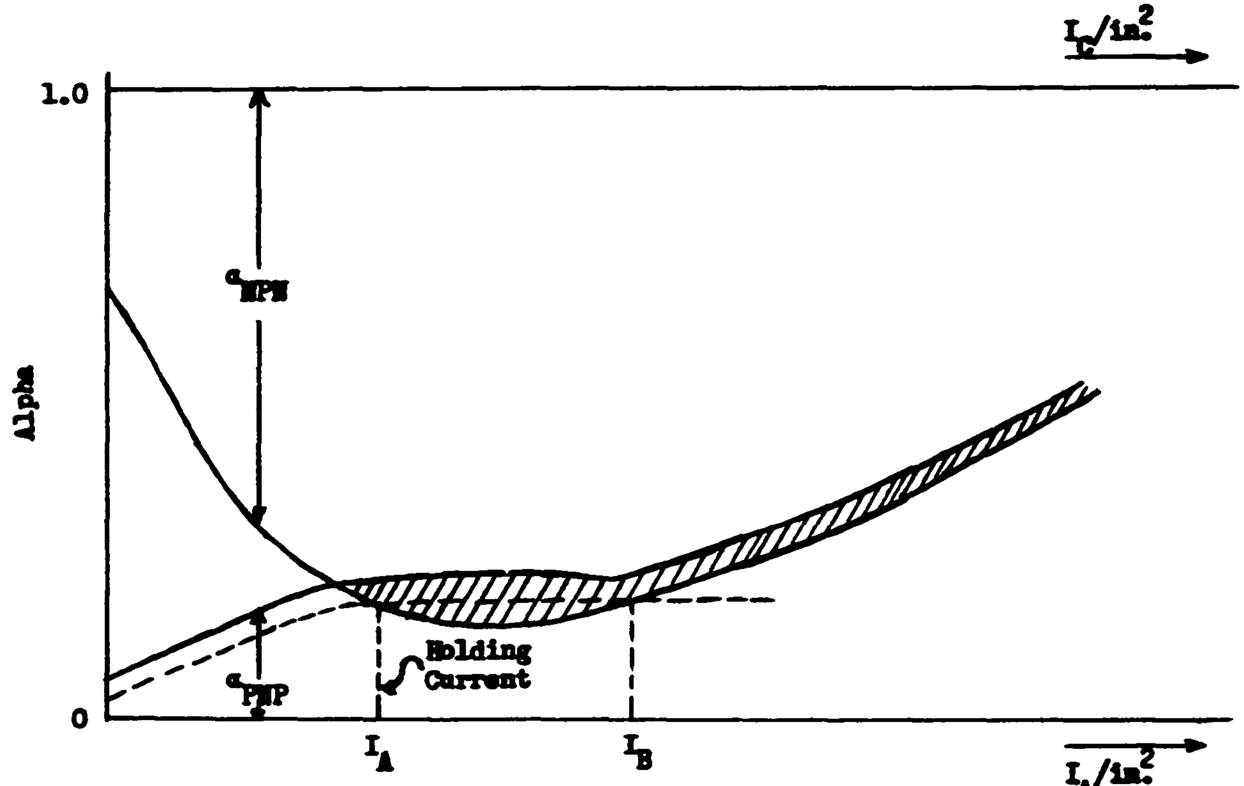


Figure 3- PNPN Structure of Wide N-base and Different P-base Widths vs. PNP and NPN Alphas

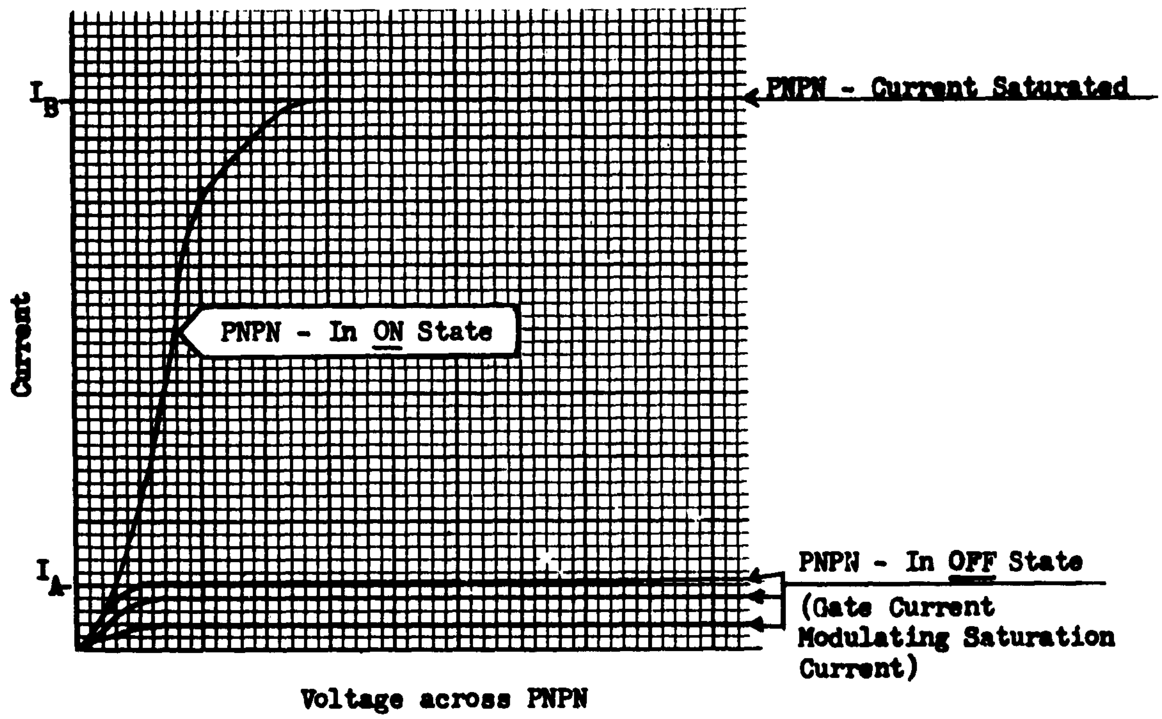


Figure 4- Load Current vs. Voltage Across PNPN Structure

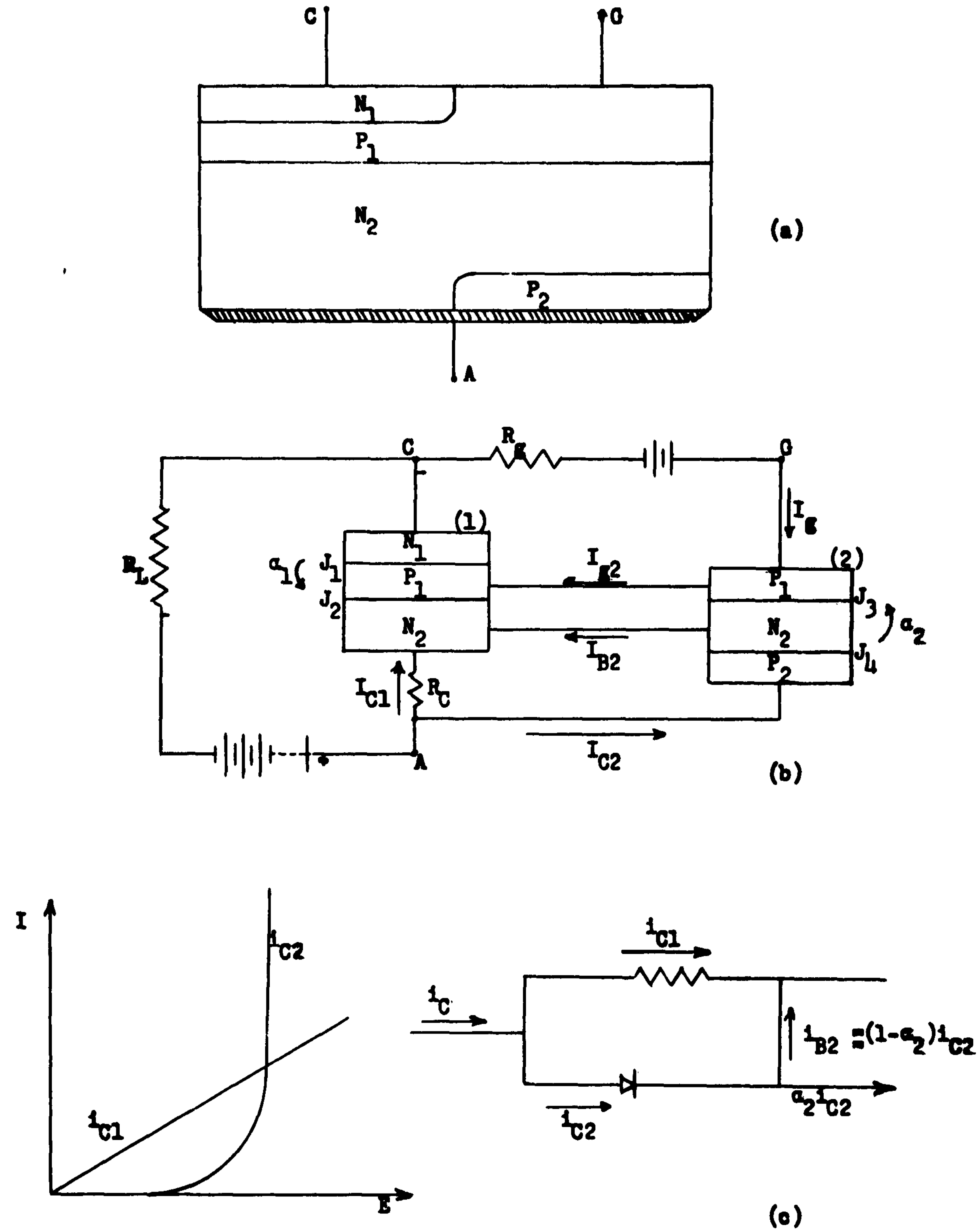


Figure 5- Integrated PNPN-NPN Structure

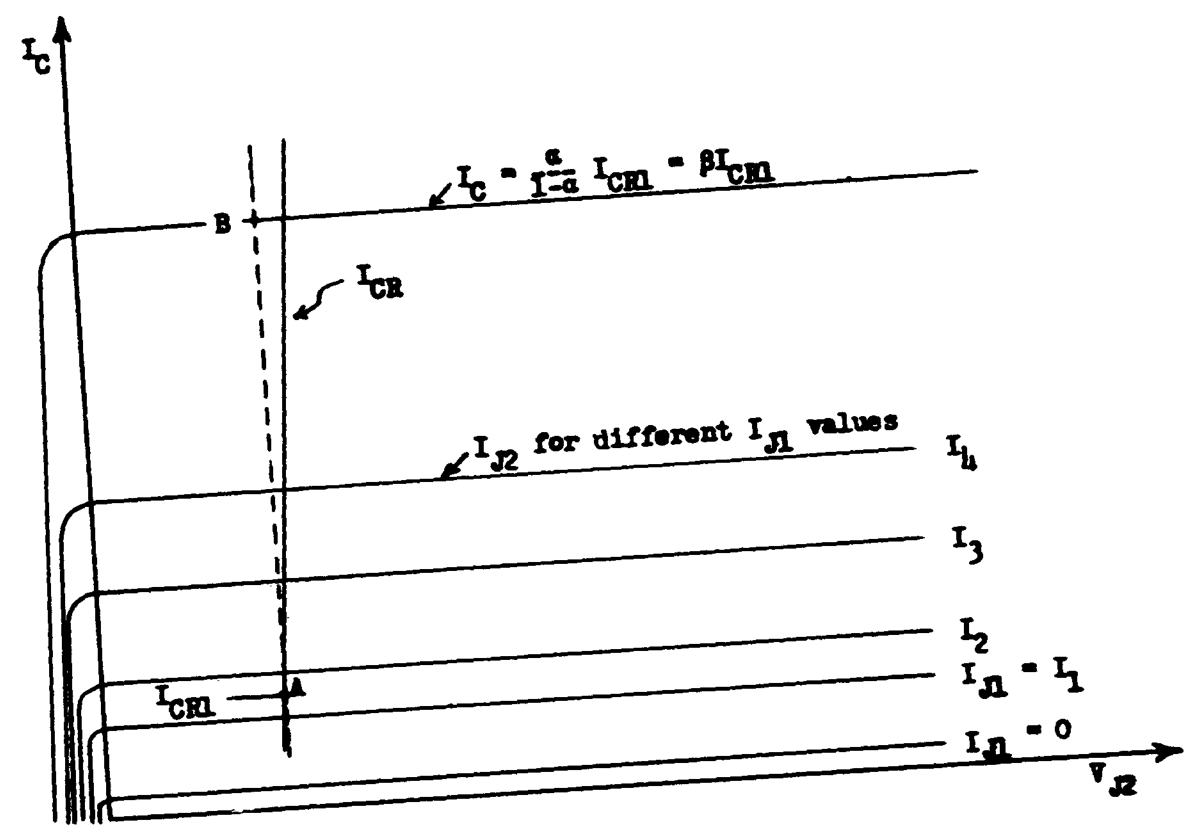


Figure 6- Collector Currents

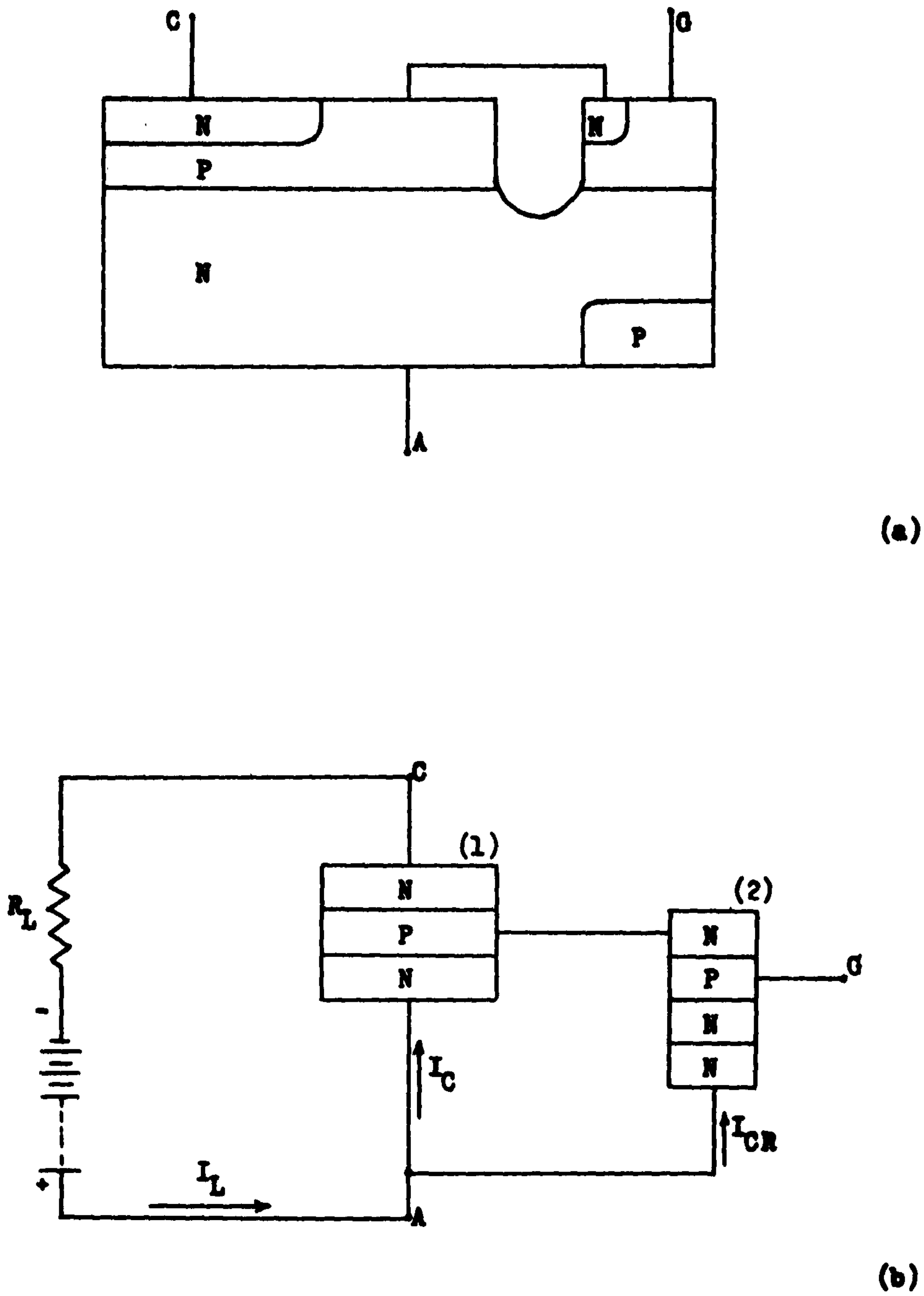


Figure 7- Composite PNPN-NPN Structure

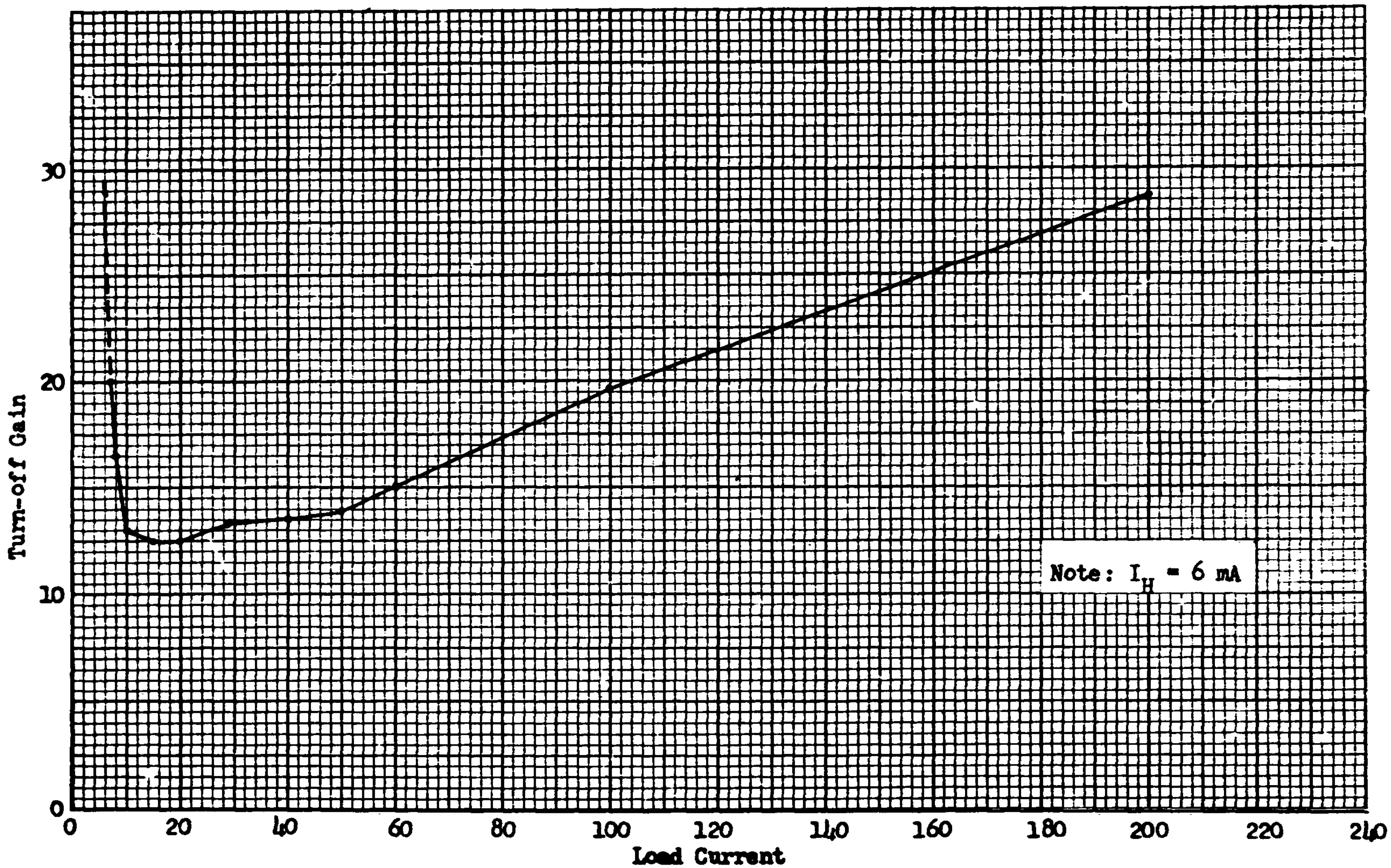


Figure 8- Turn-off Gain vs. Load Current
(ZJ203-P Lapped)

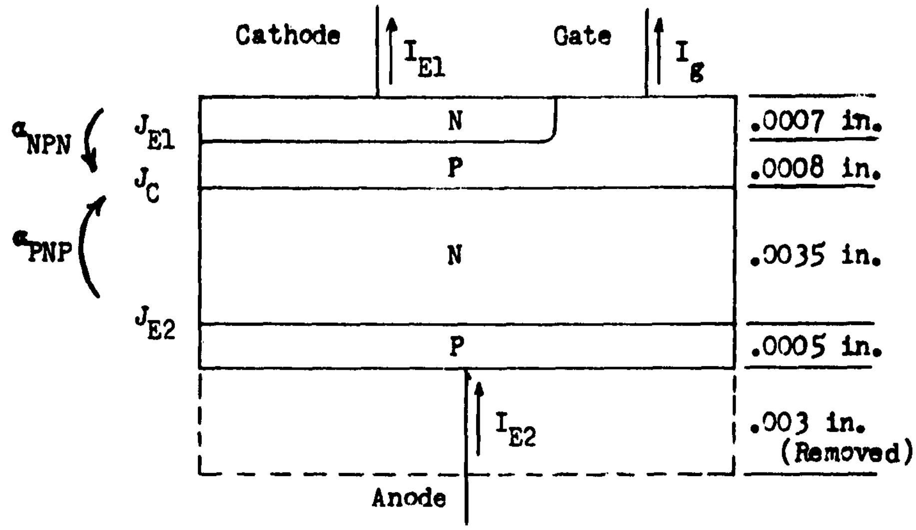


Figure 9- PNPN Structure with Deep Gallium Diffusion on One Side

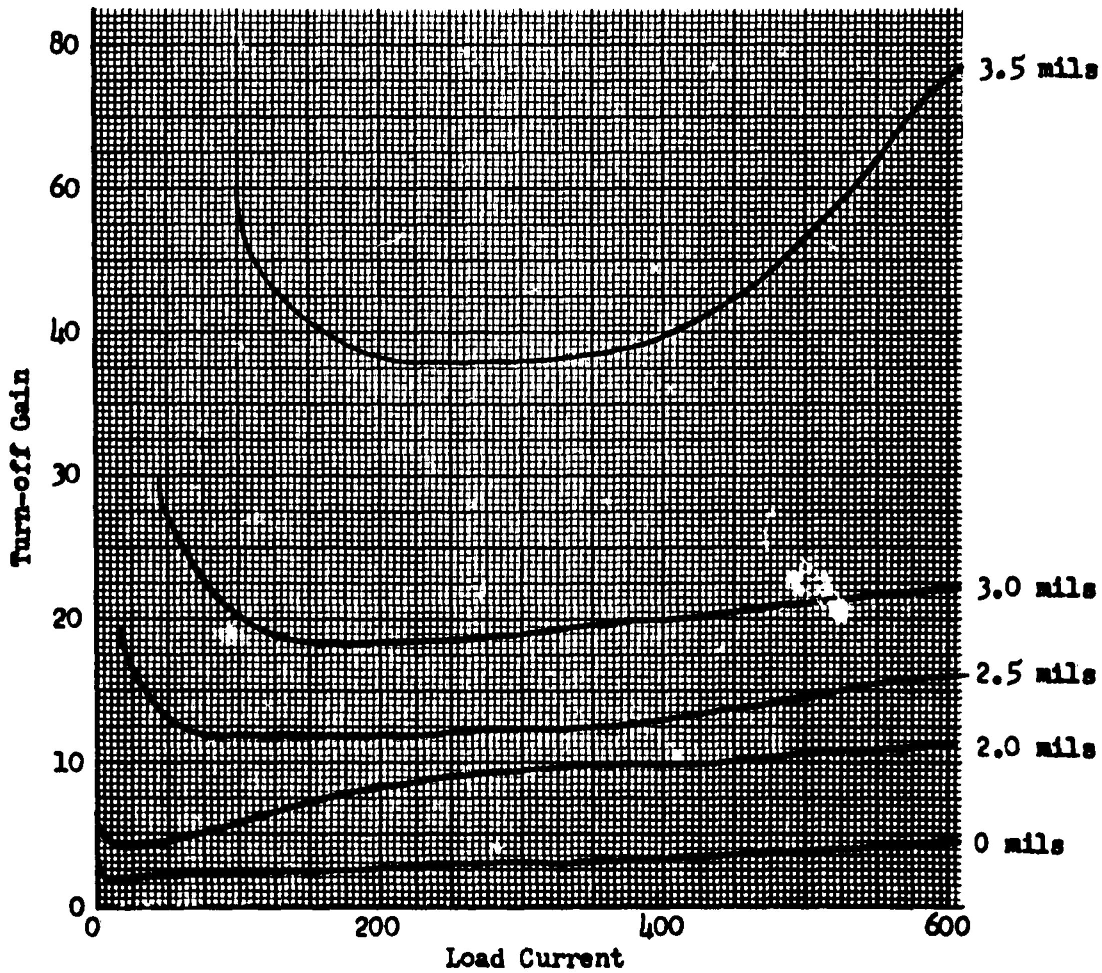


Figure 10- Turn-off Gain vs. Load Current for Varying Amounts of P-type Emitter Removed (Original Depth of P-layer was 4 mils)

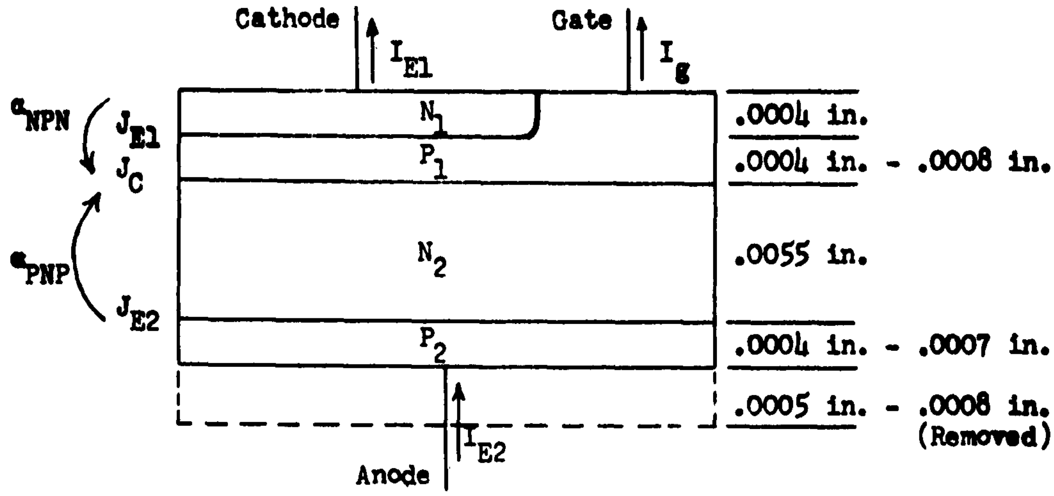


Figure 11- PNPN Structure with Wide N-base and Different P-base Widths

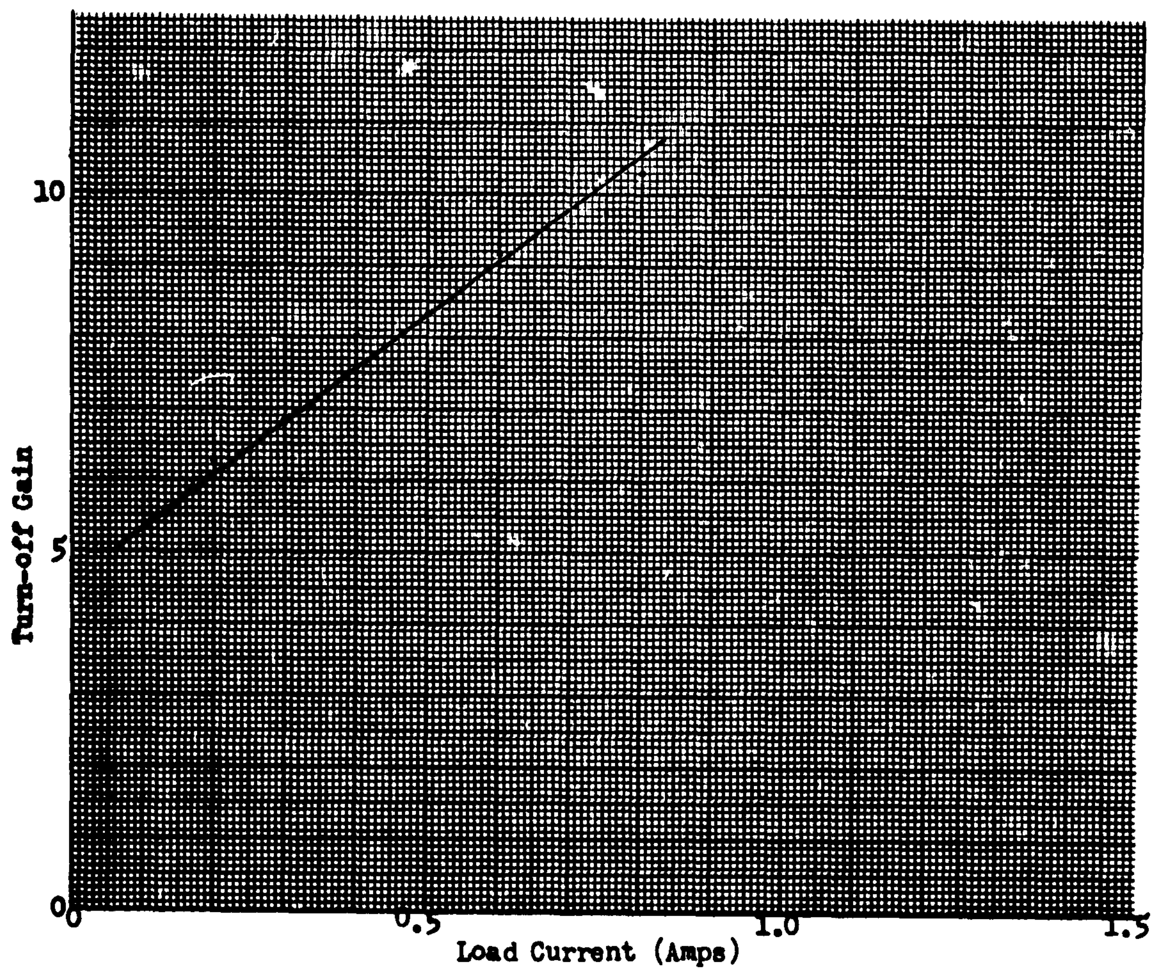


Figure 12- Turn-off Gain vs. Load Current (Typical for 3 amp Stud Mounted Device)

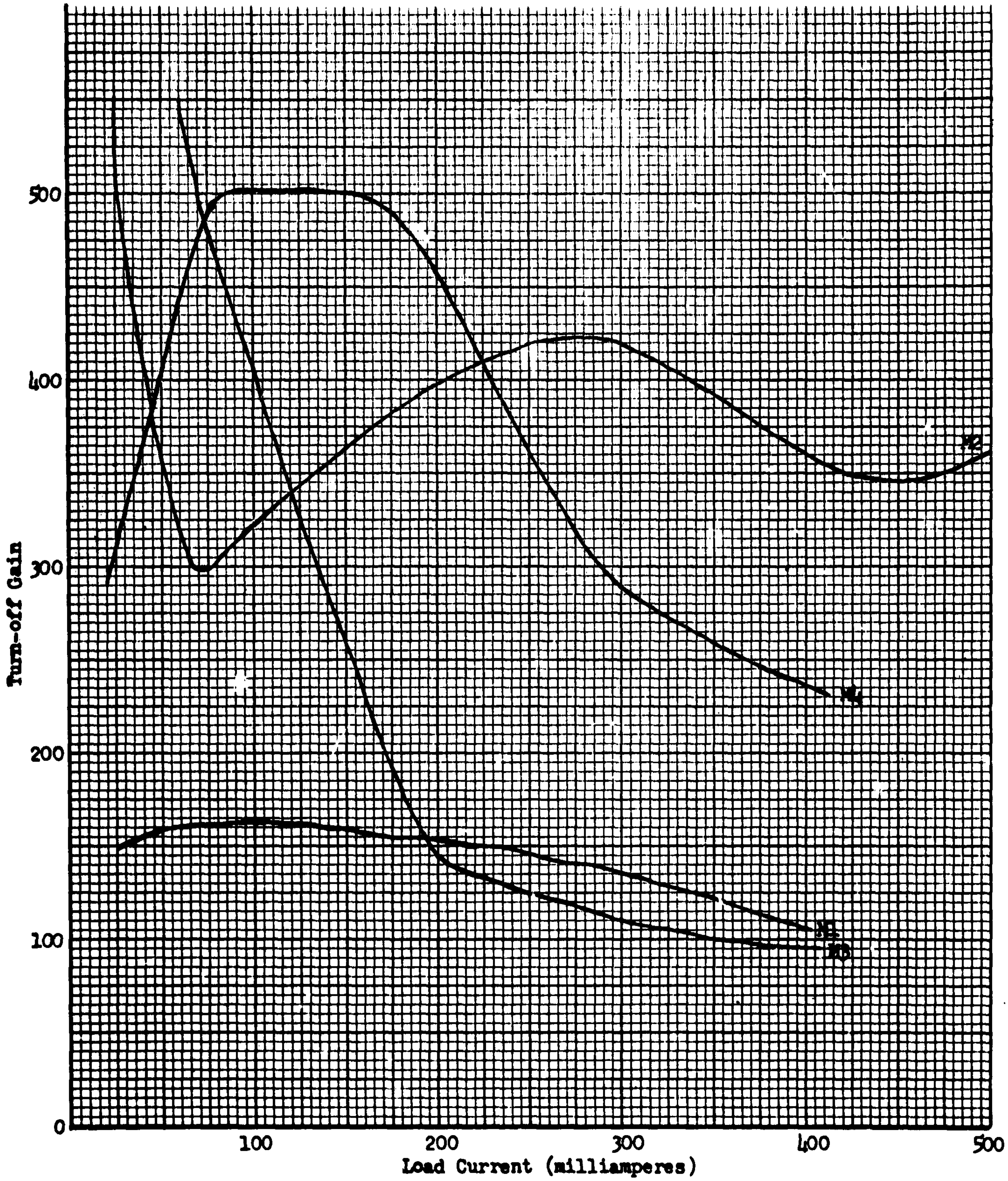


Figure 13. Turn-off Gain vs. Load Current

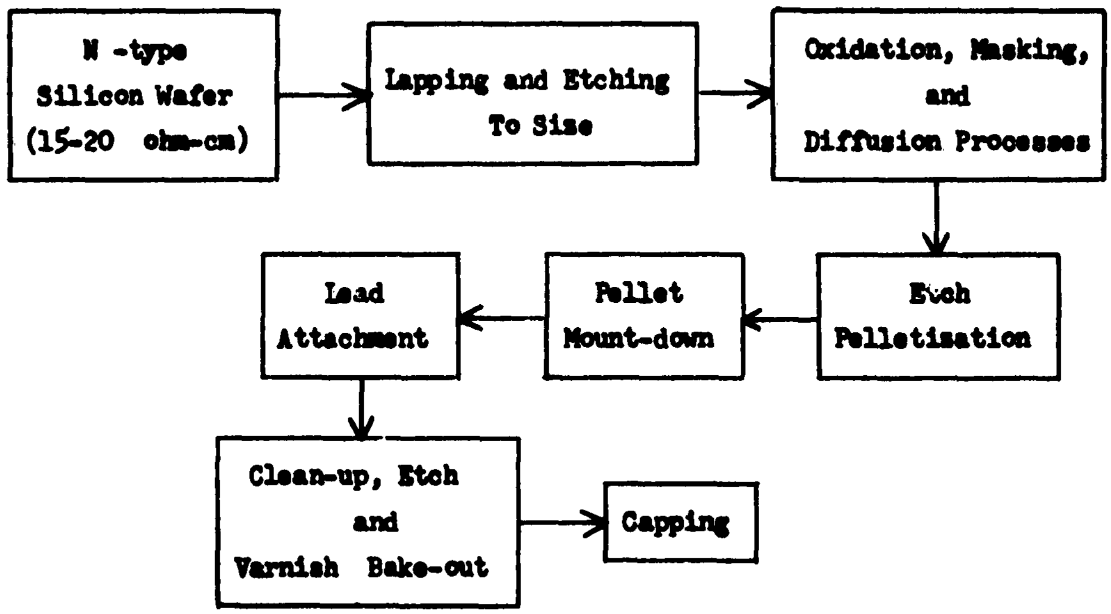


Figure 14- Flow Chart of Device Assembly

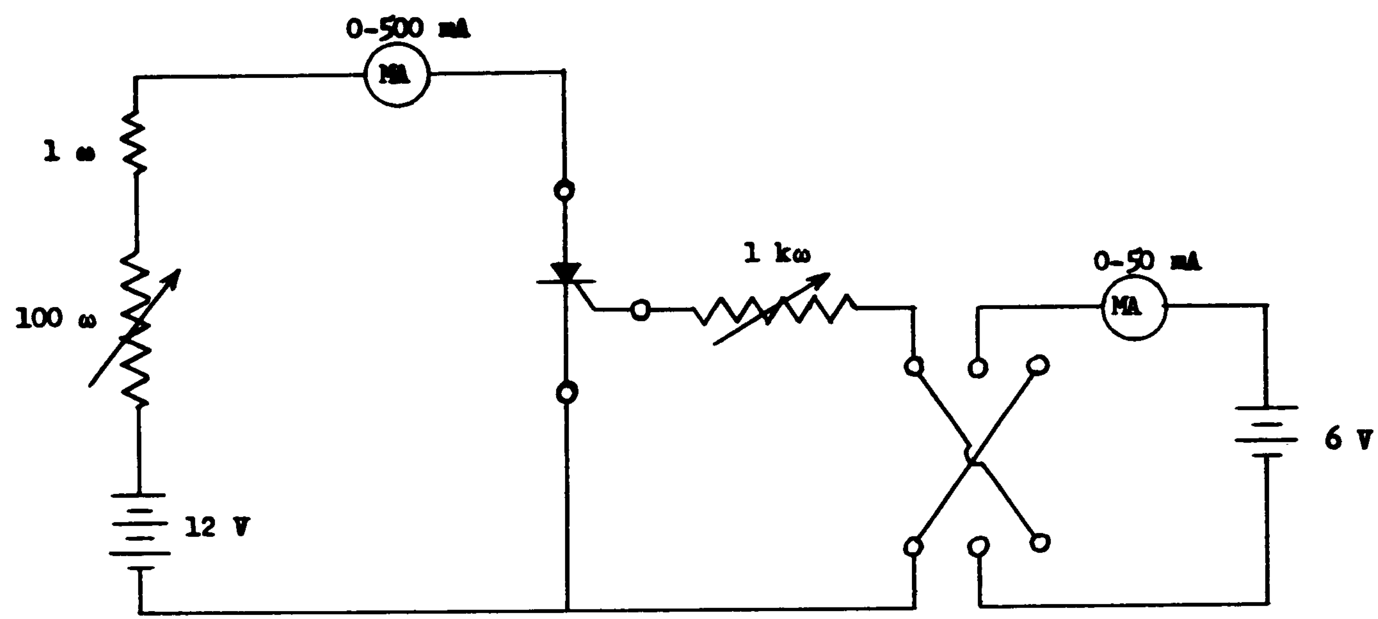


Figure 15- Static Test Circuit for Turn-off Controlled Rectifiers

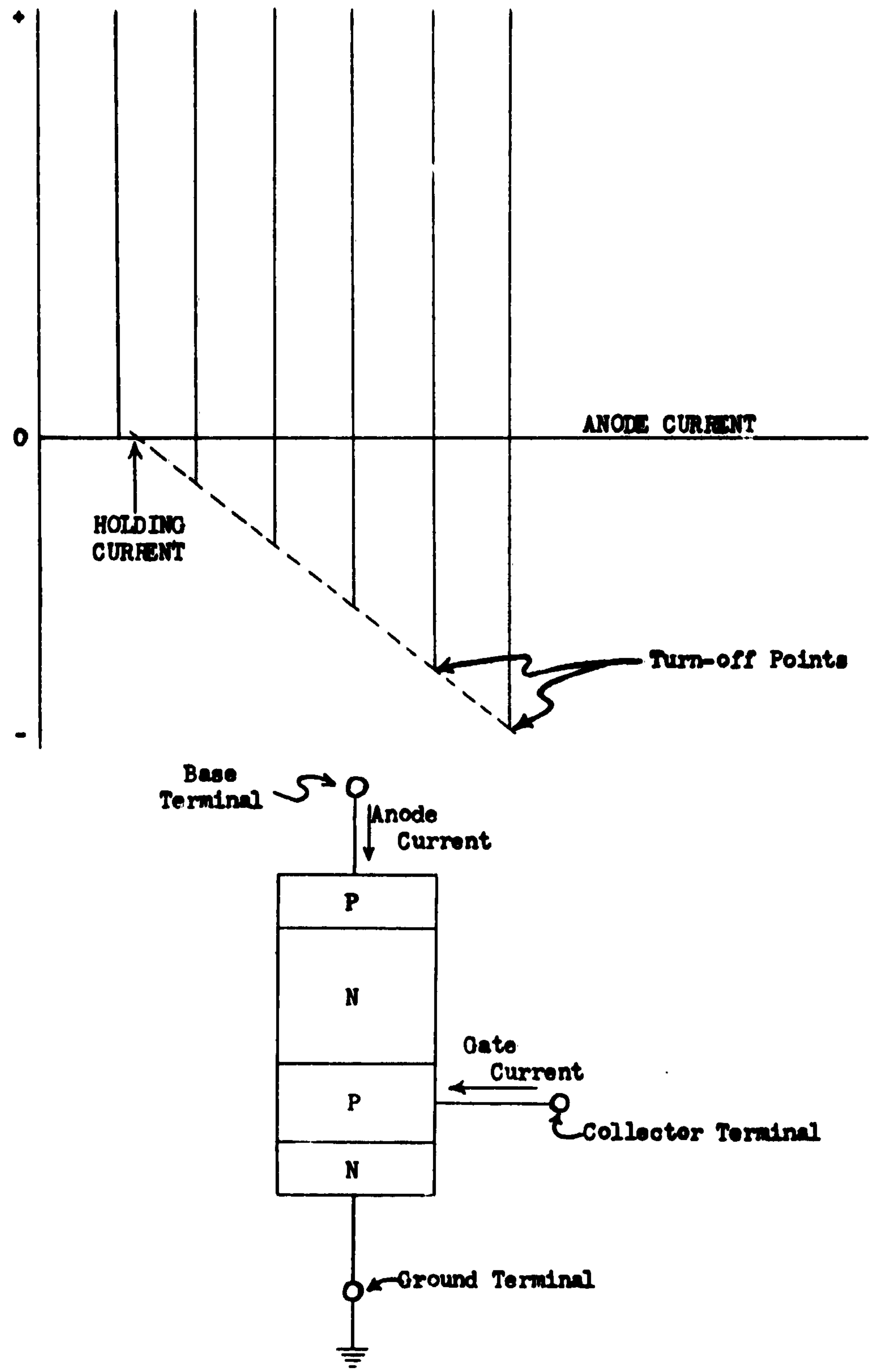


Figure 16- Gate Current vs. Anode Current

Vertical: 2 mA/Div.

Horizontal: 20 mA/Div.

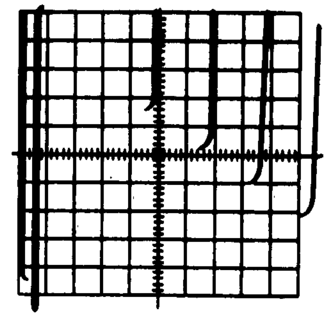
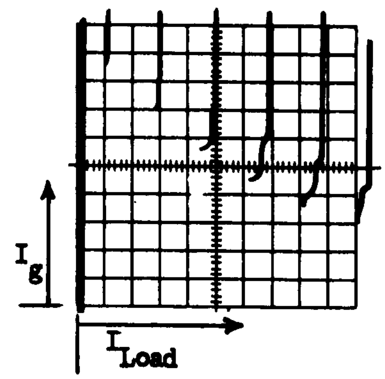
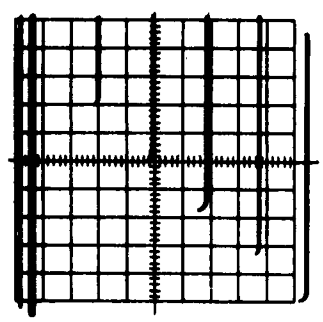


PHOTO NO. A2

Vertical: 5 mA/Div.

Horizontal: 100 mA/Div.

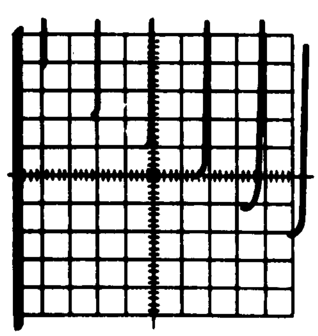




Vertical: 2 mA/Div.

Horizontal: 20 mA/Div.

PHOTO NO. A7



Vertical: 10 mA/Div.

Horizontal: 100 mA/Div.

Figure 17- Gate Turn-off Curves

SECTION V

Conclusions

Controlled rectifiers with turn-off gains ranging from 10 to 60 can be readily made. Under this contract,devices with a maximum rating of one ampere have been made. The same design criteria can be used to make higher current devices. This was demonstrated by making a few three ampere stud-mounted units. There is no reason to believe that still higher current devices with the same general characteristics cannot be made. It should be noted that some of the characteristics of these devices will be different than those of standard controlled rectifiers, e.g. turn-on currents, holding currents and forward voltage drops will be higher while the reverse blocking voltage will be lower. In addition, turn-off times will be faster.

Controlled rectifiers with much higher turn-off gains (500 or higher) can be obtained by combining three and four layer devices into one structure. The ultimate gain of such structures will be limited by the gains of the individual sub-structures and the number of them used in cascade. The higher gain of such structures is the result of the multiplication of the gains of the sub-structures. Optimization of characteristics will depend on the specific requirements of the controlled rectifier, e.g. ratio of impedance between the on and off states, blocking voltage, etc.

SECTION VI

Recommendations

If high turn-off gains are required, a combination of turn-off controlled rectifier (as described in this report) and a transistor of appropriate gain can be used in a circuit arrangement. However, if a single component with very high turn-off gain is desired, further work on combining the criteria of turn-off controlled rectifiers and power transistors will be required. In order to achieve such a component, many process refinements in the area of pellet mount-down, contacts, etching, and stabilization will have to be explored.

SECTION VII

IDENTIFICATION OF PERSONNEL

A. Technical Effort Expended

Professional Personnel:

F. E. Gentry

J. Moyson

J. Petruzella

E. J. Mets

	4258 Man Hours
Technicians:	2040 Man Hours
Shop Work:	45 Man Hours

B. Biographies

Biographical summaries of key personnel have been presented in previous Quarterly Progress Reports. There are no additional personnel associated with this contract.

AD ______________ DIV. ______________

Rectifier Components Department,
General Electric Co., Auburn, N. Y.

INVESTIGATIONS OF ELECTRONICALLY CONTROLLABLE TURN-OFF CONTROLLED RECTIFIERS — J. Moyson and J. Petruzella

Final Report, 30 June 1960 to 30 June 1961, 75 pp., 17 Illus., 0 Tables, Signal Corps Contract DA #36-039-SC-85062, DA Project No. 3A99-21-001, Unclassified Report.

This report summarizes the work which was performed under a research and development program toward the realization of a high gain gate "turn-off" controlled rectifier. Basically, two types of turn-off structures evolved, 1.) the modified PNPN and 2.) the composite PNPN-NPN. A maximum turn-off gain of 75 was achieved using the modified PNPN structure whereas turn-off gains up to 500 were observed on the composite PNPN-NPN structure. Details of both structures are discussed including theory of operation, fabrication techniques, experimental data and results, measurements and test equipment. Finally, overall conclusions and recommendations are presented based on the work of this program.

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